Draft version November 15, 2006
Preprint typeset using LaTeX style emulateapj v. 10/10/03

COSMIC DUST INDUCED FLUX FLUCTUATIONS: BAD AND GOOD ASPECTS

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Draft version November 15, 2006

ABSTRACT

Cosmic dust extinction alters the flux of type Ia supernovae. Inhomogeneities in the dust distribution induce correlated fluctuations of the SN fluxes. We find that such correlation can be up to 60% of the signal caused by gravitational lensing magnification, with an opposite sign. Therefore if not corrected, cosmic dust extinction is the dominant source of systematic uncertainty for future SNe Ia lensing measurement limiting the overall S/N to be $\lesssim 10$. On the other hand, SN flux correlation measurements can be used in combination with other lensing data to infer the level of dust extinction. This will provide a viable method to eliminate gray dust contamination from the SN Ia Hubble diagram.

Subject headings: Cosmology: large scale structure-gravitational lensing- supernovae: general-dust: extinction

1. INTRODUCTION

Gravitational lensing causes several observable effects such as distortion of galaxy shape (*cosmic shear*), variation of galaxy number density (*cosmic magnification*) and mode-coupling in cosmic backgrounds. Over the upcoming years measurements of these effects will provide an accurate mapping of the matter distribution in the universe (for reviews see Bartelmann & Schneider (2001); Refregier (2003)).

Recently, several other lensing reconstruction methods have been proposed. One possibility is to measure the spatial correlation of lensing induced supernova (SN) flux fluctuations. In fact due to lensing magnification[1], the SN flux is altered such that $F \rightarrow F\mu \simeq F(1+2\kappa)$, where F is the intrinsic SN flux, μ is the lensing magnification and κ is the lensing convergence. Intrinsic fluctuations of the SN flux are random (analogous to intrinsic galaxy ellipticities in cosmic shear measurement). In contrast those induced by lensing magnification (see e.g. Kantowski et al. (1995); Frieman (1996); Holz (1998); Dalal et al. (2003)) are correlated with the overall matter distribution (analogous to the shear signal). Therefore the lensing signature can be inferred either from spatial correlation measurements of SN fluxes (Cooray et al. 2006) or from the root-mean-square of flux fluctuations of high redshift SNe for which the lensing signal is dominant (Dodelson & Vallinotto 2006).

Gravitational lensing also induces scatter in the galaxy fundamental plane through magnification of the effective radius, $R_e \rightarrow R_e\mu^{1/2} \simeq R_e(1+\kappa)$. Since intrinsic scatters in the fundamental plane are random, spatial correlation measurements can be used to infer the lensing signal (Bertin & Lombardi 2006). A similar analysis can be applied to the Tully-Fisher relation as well.

Astrophysical effects may limit the accuracy of these methods. For instance extinction by cosmic gray dust can be an important source of systematic uncertainty. This is because dust absorption changes the apparent SN flux and may induce correlation of the flux fluctuations. It also induces scatters in the fundamental plane by dimming the galaxy surface brightness and affects the Tully-Fisher relation through dimming the galaxy flux. These effects potentially cause non-negligible systematics in the corresponding lensing measurements.

Although the existence of gray dust in the intergalactic medium (IGM) remains untested, this scenario could account for the metal enrichment of the IGM (Bianchi & Ferrara (2005) and reference therein). Testing the gray dust hypothesis is also relevant for cosmological parameter inference from SN Ia luminosity distance measurements. Recently Corasaniti (2006) has pointed out that gray dust models which pass current astrophysical constraints can induce a $\sim 20\%$ bias in the estimate of the dark energy equation of state w using the Hubble diagram of future SN Ia experiments.

In this paper, we study the impact of cosmic gray dust on SN lensing measurements, under the optimistic assumption that contaminations of reddening dust can be perfectly corrected. The effects on lensing reconstruction based on the fundamental plane and the Tully-Fisher relation can be estimated similarly. For supernova, the key point is that extinction caused by dust inhomogeneities along the line of sight causes flux fluctuations which are anti-correlated with the lensing magnification signal and thus wash-out its imprint. In particular we find that dust induced correlation can bias SN lensing measurements by $10-60\%$. Therefore this effect is likely to be the dominant source of systematics for future SN surveys characterized by large sky coverage and sufficiently high surface number density. If not corrected, the dust induced correlation would limit the signal-to-noise to S/N $\lesssim 10$. This is low compared to the S/N achieved by current cosmic shear measurements

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[1] Throughout this paper, the term lensing magnification refers to both the cases of magnification ($\mu > 1$) and de-magnification ($\mu < 1$). To be more specific, the spatial correlation functions and the corresponding power spectra (C_κ and $C_{\kappa\delta_\tau}$) investigated hereafter are averaged over the full distribution of μ.

(e.g. Jarvis et al. (2005); Van Waerbeke et al. (2005); Hoekstra et al. (2005)) and that of proposed methods such as CMB lensing (Seljak & Zaldarriaga 1999; Zaldarriaga & Seljak 1999; Hu 2001; Hu & Okamoto 2002), 21cm background lensing (Cooray 2004; Pen 2004; Zahn & Zaldarriaga 2005; Mandel & Zaldarriaga 2005) and cosmic magnification of 21cm emitting galaxies (Zhang & Pen 2005, 2006).

Nevertheless we suggest that measurements of the SN flux correlation still carry valuable information. In fact in combination with other lensing data they will provide a viable method to detect and eliminate cosmic gray dust contamination from future SN Ia luminosity distance measurements.

2. DUST INDUCED FLUX FLUCTUATIONS

The observed flux of a SN Ia at redshift z in the direction $\hat{n}$ of the sky is

$$F^{\rm obs}(\hat{n},z)=F\mu\, e^{-\tau}\ , \tag{1}$$

where F is the intrinsic flux and τ the optical depth caused by dust extinction along the line of sight. The lensing magnification can be written as $\mu\equiv 1/[(1-\kappa)^2-\gamma^2]\simeq 1+2\kappa$ with κ and γ being the lensing convergence and shear respectively. In the presence of dust density inhomogeneities, the optical depth can be decomposed in a homogeneous and isotropic part $\bar{\tau}$ and a fluctuation $\delta\tau$ ($\tau\equiv\bar{\tau}+\delta\tau$). To first order, Eq. (1) reads as

$$F^{\rm obs}(\hat{n},z)\simeq F e^{-\bar{\tau}(z)}\left[1+2\kappa(\hat{n},z)-\delta\tau(\hat{n},z)\right]. \tag{2}$$

It is worth noticing that the lensing and dust extinction terms have opposite sign. Since $\bar{\mu}=0$ (ensemble average) and $\bar{\kappa}=0$, the average flux of a SN Ia sample in a given redshift bin is $\bar{F}^{\rm obs}(z)\simeq\bar{F}e^{-\bar{\tau}(z)}$.

The angular correlation of the flux fluctuations can be inferred from the estimator $\delta_F(\hat{n},z)\equiv F^{\rm obs}/\bar{F}^{\rm obs}-1$ (Cooray et al. 2006). From Eq. (2) we then have $\delta_F=2\kappa-\delta\tau$, hence δ_F provides an estimate of the gravitational lensing only if fluctuations in the optical depth are negligible.

The lensing convergence κ is related to the 3D matter overdensity δ_m by

$$\kappa=\frac{3}{2}\Omega_m\frac{H_0^2}{c^2}\int\delta_m\, W(\chi,\chi_s)d\chi\ , \tag{3}$$

where $W(\chi,\chi_s)$ is the lensing geometry function. For a flat universe $W(\chi,\chi_s)=(1+z)\chi(1-\chi/\chi_s)$, with χ and χ_s the comoving diameter distance to the lens and source respectively.

Following the derivation of Corasaniti (2006) the average optical depth to redshift z is

$$\bar{\tau}(z)=\frac{1}{2.5\log e}\int_0^z\frac{d\bar{A}}{dz'}c\, dz', \tag{4}$$

with c the speed of light and

$$\frac{1}{2.5\log e}\frac{d\bar{A}}{dz}=\frac{3}{4\varrho}\frac{\bar{\rho}_{\rm d}(z)}{(1+z)H(z)}\int Q_m^\lambda(a,z)N(a)\,\frac{da}{a}, \tag{5}$$

where $\bar{\rho}_d$ is the average dust density, ϱ is the grain material density, a is the grain size, Q_m^λ is the extinction efficiency factor at the rest-frame wavelength λ which depends on the grain size and complex refractive index m, and $N(a)$ is the size distribution of dust particles. The extinction efficiency factor is computed by solving numerically the Mie equations for spherical grains (Barber & Hill 1990). Since dust particles are made of metals we estimate the evolution of the average cosmic dust density $\bar{\rho}_d$ from the redshift dependence of the average cosmic metallicity as inferred by integrating the star formation history (SFH) the Universe. Such a modeling is an extention of that presented in Aguirre (1999) and Aguirre & Haiman (2000), since in addition to estimating the amount of cosmic dust density in terms of the measured SFH, it accounts for the physical and optical properties of the dust grains.

This approach differs from that used in some of the SN Ia literature (see for instance Riess et al. (2004)). In these studies the cosmic dust dimming is estimated by modeling the evolution of dust density as a redshift power law with different slopes corresponding to different cosmic dust models. More importantly these studies assume the empirical interstellar extinction law, tipically in the form inferred by Cardelli et al. (1989). However cosmic dust particles undergo very different selection mechanisms compared to interstellar grains and therefore are unlikely to cause a similar extinction.

In this perspective our modeling is rather robust, since the cosmic dust absorption is computed from first principles and in terms of astrophysical parameters which can be measured through several observations, such as X-ray quasar halo scattering (see Paerels et al. 2002) or high resolution measurements of the Far Infrared Background (FIRB) (Aguirre & Haiman 2000). For more details on these cosmic dust models and their cosmological impact we refer to Corasaniti (2006).

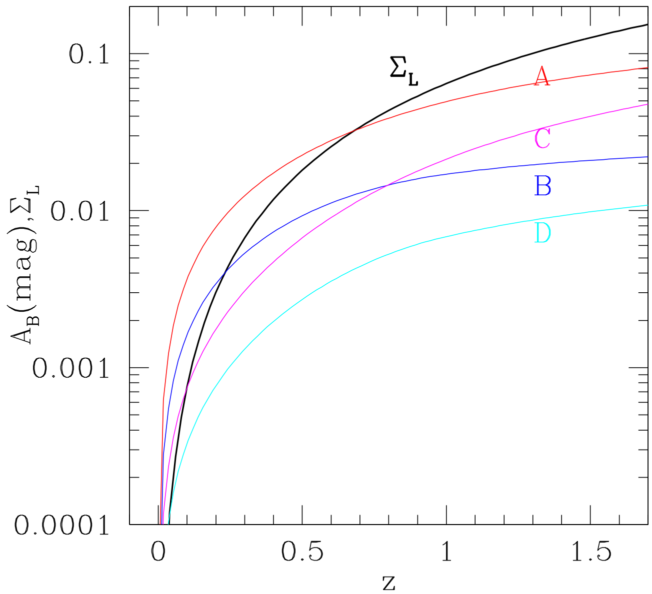

FIG. 1.— The lensing normalized matter surface density Σ_L and the B-band dust extinction A_B for different dust models (see text). Since A_B and Σ_L are comparable, dust extinction effects cannot be neglected in lensing measurements of SN flux correlation.

The fluctuation in the optical depth is then given by

$$\delta\tau = \frac{1}{2.5\log e}\int_0^z \frac{d\bar{A}}{dz'}\delta_{\rm d}(z')c\,dz', \quad (6)$$

where $\delta_{\rm d}$ is the fractional dust density perturbation. The resulting auto-correlation power spectrum of δ_F is:

$$\frac{1}{4}C_{\delta_F}(l) = C_\kappa + \frac{1}{4}C_{\delta\tau} - C_{\kappa\delta\tau}, \quad (7)$$

where C_κ, $C_{\delta\tau}$, $C_{\kappa\delta\tau}$ are the angular power spectra of κ, $\delta\tau$, and the κ-$\delta\tau$ cross correlation. Using the Limber's approximation these read as (Limber 1954; Kaiser 1998):

$$\frac{l^2C_\kappa}{2\pi} = \frac{\pi}{l}\left[\frac{3\Omega_m H_0^2}{2c^2}\right]^2\int \Delta^2_\delta\left(\frac{l}{\chi},z\right)W^2(\chi,\chi_s)\chi d\chi\ , \quad (8)$$

$$\frac{l^2C_{\delta\tau}}{2\pi} = \frac{\pi}{l}\left[\frac{1}{2.5\log e}\right]^2\int \Delta^2_{\delta_d}\left(\frac{l}{\chi},z\right)\left[\frac{d\bar{A}}{d\chi}\right]^2\chi d\chi\ , \quad (9)$$

and

$$\frac{l^2C_{\kappa\delta\tau}}{2\pi} = \frac{\pi}{l}\frac{3\Omega_m H_0^2}{5c^2\log e}\int \Delta^2_{\delta\delta_d}\left(\frac{l}{\chi},z\right)W(\chi,\chi_s)\frac{d\bar{A}}{d\chi}\chi d\chi, \quad (10)$$

where $\Delta^2_\delta \equiv k^3P_\delta(k)/2\pi^2$ is the dimensionless matter density variance and P_δ is the matter density power spectrum. The nonlinear Δ^2_δ is calculated using the Peacock-Dodds fitting formula (Peacock & Dodds 1996). $\Delta^2_{\delta\delta_d}$ and $\Delta^2_{\delta_d}$ are defined analogously. The spatial distribution of IGM dust is not known, the simplest assumption is that dust traces the total mass distribution. In such case $\Delta^2_{\delta_d} = b_d^2\Delta^2_\delta$ and $\Delta^2_{\delta\delta_d} = b_d\Delta^2_\delta$, where b_d is the dust bias.

Defining $\Sigma_L \equiv \frac{3}{2}\Omega_m\frac{H_0^2}{c^2}\int W(\chi,\chi_s)d\chi$, one has $\delta\tau/\kappa \sim b_d\bar{A}/\Sigma_L$, hence $C_{\delta\tau}/C_\kappa \sim b_d^2(\bar{A}/\Sigma_L)^2$ and $C_{\kappa\delta\tau}/C_\kappa \sim b_d(\bar{A}/\Sigma_L)$. This indicates that cosmic dust contamination is negligible only if $\bar{A}(z) \ll \Sigma_L(z)$.

We adopt a flat ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, $\Omega_b = 0.04$, $\sigma_8 = 0.9$ and the primordial power index $n = 1$. We assume the BBKS transfer function (Bardeen et al. 1986). For the dust extinction we limit our analysis to a test-bed of four cosmic dust models studied in Corasaniti (2006). These are characterized by model parameter values motivated by astrophysical considerations. In particular the particle size distribution is in the range $0.05 - 0.2\,\mu m$, consistently with the fact that smaller grains are distroyed by sputtering, while larger ones remain trapped in the gravitational potential of the host galaxy (Ferrara et al. (1991); Shustov & Vibe (1995); Davis et al. (1998)). The grain composition consisting of Silicate or Graphite particles and we consider both low and high star formation history scenarios.

Models A and B refer to Graphite particles with low and high SFH respectively, while models C and D correspond to Silicate grains. The total dust density for these models is within the limits imposed by the DIRBE/FIRAS data (Aguirre & Haiman 2000) and concides with the upper limit obtained from the analysis of X-ray quasar halo scattering (Paerels et al. 2002). These gray dust models cause little reddening of the incoming light and induce a color excess in the optical and near-IR bands smaller than 0.01 mag.

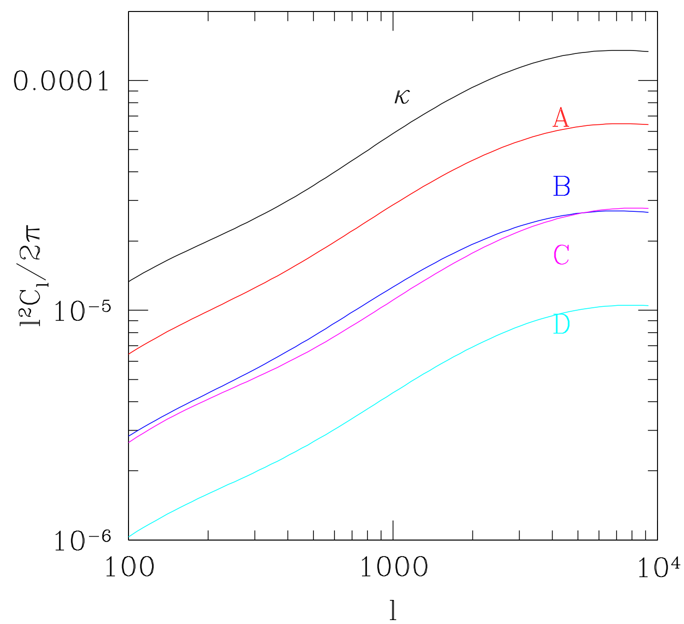

FIG. 2.— Lensing and dust contamination power spectra. The upper line is the lensing convergence $l^2C_\kappa/2\pi$. Other lines are $C_{\kappa\delta\tau} - C_{\delta\tau}/4$ for dust model A, B, C and D, respectively with $b_d = 1$. We have assumed all SNe to be at $z_s = 1$. Clearly, the existence of cosmic dust would degrade or even prohibit measurement of the lensing signal.

A further assumption concerns the gray dust spatial distribution, for which we have little knowledge of. This model uncertainty may affect the results presented in this paper significantly. One can imagine an extreme case where gray dust distributes homogeneously. Then there will be no fluctuations in τ and thus no induced correlation in SN flux fluctuations. However, current understanding of gray dust formation implies that gray dust is associated with the overall matter distribution. So a more appropriate treatment of gray dust distribution is the bias model $\delta_d = b_d\delta_m$, as adopted in this paper. Although it is natural to expect b_d to be redshift and scale dependent, since we have little knowledge of it for simplicity we assume $b_d = 1$.

From Fig. 1 we can see that Σ_L is comparable to the B-band dust extinction $\bar{A}$, hence dust contamination cannot be neglected. Therefore $C_{\delta\tau}$ and $C_{\kappa\delta\tau}$ in Eq. (7) are source of systematic errors which need to be corrected if we aim to measure the convergence power spectrum.

In Fig. 2 we plot the lensing convergence power spectrum $l^2C_\kappa/2\pi$, and the dust contamination power spectrum $C_{\kappa\delta\tau} - C_{\delta\tau}/4$ for our test-bed of dust models for sources at $z_s = 1$. We find that $C_{\delta\tau}$ is smaller than $C_{\kappa\delta\tau}$, mainly due to the $1/4$ prefactor. Since $C_{\kappa\delta\tau}$ has an opposite sign to the lensing signal in Eq. (7), its overall effect is to suppress the spatial correlation of SN Ia flux fluctuations and consequently diminish the variance and covariance of flux fluctuations. Since statistical errors on cosmological parameters constraints from SNe Ia Hubble diagram are proportional to the square root of the vari-

Table 1
The relative error caused by extinction with respect to lensing, $\eta = |C_{\kappa\delta\tau} - C_{\delta\tau}/4|/C_\kappa$ at different source redshifts for our test-bed of dust models. η is roughly independent of multipole l, since shapes of C_κ, $C_{\kappa\delta\tau}$ and $C_{\delta\tau}$ are very similar.

source redshift z_s	Graphite high SFH Model A	Graphite low SFH Model B	Silicate high SFH Model C	Silicate low SFH Model D
0.5	0.65	0.33	0.24	0.11
1.0	0.45	0.20	0.21	0.08
1.7	0.36	0.13	0.19	0.06

ance and covariance (see e.g. Cooray et al. (2006a) for discussions), the existence of cosmic dust extinction fluctuations decreases the statistical uncertainties, though the mean dust extinction will induce a systematic bias unless corrected.

Dust contamination can be quantified by the ratio $\eta \equiv |C_{\kappa\delta\tau} - C_{\delta\tau}/4|/C_\kappa$. Since both κ and $\delta\tau$ trace the same large scale structure (enforced by the simplification b_d =const.), the multipole dependence of C_κ, $C_{\delta\tau}$ and $C_{\kappa\delta\tau}$ are similar such that η is roughly constant. In table 1 we list its values for sources at redshift $z_s = 0.5, 1.0$ and 1.7 respectively. As it can be seen, model A causes the largest contamination inducing a systematic error as large as 60% of lensing signal. Even for model D the contamination is still $\sim 10\%$, which is comparable to the statistical error expected from future SN Ia lensing measurements. Consequently dust induced systematics will be the dominant source of uncertainty for this type of measurements.

Furthermore we find that the relative error can be approximated by $\eta = \beta b_d \bar{A}/\Sigma_L$, where $\beta \simeq 0.7$ with a dispersion < 0.1 over the redshifts investigated for our test-bed of dust models. This relation suggests that if we can measure η in combination with an independent lensing measurement, it would be possible to infer $\bar{A}$ given knowledge of b_d. In the next section we will discuss how these type of measurements can be used to remove cosmic dust contamination in the SN Ia Hubble diagram.

3. REMOVING COSMIC DUST CONTAMINATION

Flux fluctuations induced by lensing and extinction are small compared to intrinsic SN flux fluctuations and therefore can only be extracted statistically, except for the strongly lensed or heavily extincted SNe. Accurate lensing measurements can be obtained from a variety of astrophysical observations of cosmic shear and cosmic magnification. In combination with correlation measurements of SN fluxes these can be used to quantify the level of cosmic dust extinction and provide a viable method to remove dust systematics from the SN Ia Hubble diagram. The idea is to infer η from the comparison of C_{δ_F} and C_κ. As discussed before $\eta \simeq 0.7 b_d \bar{A}/\Sigma_L$, this would allow to measure $\bar{A}$ up to model uncertainties in b_d and measurement errors in C_{δ_F}. The estimated value of $\bar{A}$ can then be used to correct the standard-candle relation of SN Ia.

The efficiency of this method depends on the sky coverage and the SN number density of the survey. For instance in order to measure $\bar{A}$ to 10% accuracy, the overall S/N of C_{δ_F} must be $\gtrsim 10(1/\eta - 1)$. This implies that for model A, C_{δ_F} should be measured with S/N of ~ 10, while for model B, C and D, it would require a $S/N \geq$ 40-100. In the case of a survey with 10^4 SNe and covering 20 deg^2 of the sky the signal-to-noise is $S/N \sim 10$ (Cooray et al. 2006). Since $S/N \propto f_{sky}^{1/2}$ to reach $S/N =$ 40-100 requires a factor of 20-100 times higher in sky coverage and total number of observed SNe. This can be achieved by the proposed ALPACA experiment (Corasaniti et al. 2006).

Galaxy-quasar correlation measurements provide another method to estimate the level of cosmic dust extinction. For a given line of sight, dust extinction reduces the observed number of galaxies above flux F from $N(>F)$ to $N(>F\exp[\bar{\tau}+\delta\tau]) \simeq N(>F)[1-\alpha(\bar{\tau}+\delta\tau)]$. Here, $\alpha = -d\ln N/d\ln F$ is the (negative) slope of the intrinsic galaxy luminosity function $N(>F)$ and we have assumed $\tau \ll 1$. Thus dust inhomogeneities induce a fractional fluctuation $-\alpha\delta\tau$ in the galaxy number density. Since $\delta\tau$ is correlated with the matter density field, dust extinction induces a correlation between foreground galaxies and background galaxies (quasars) such that $w_{fb}(\theta) = -\alpha\langle\delta\tau(\theta')\delta_g^f(\theta'+\theta)\rangle$. Here, δ_g^f is the foreground galaxy number overdensity. On the other hand, lensing induced fluctuations in galaxy number density are $2(\alpha-1)\kappa$ (Bartelmann & Schneider 2001), where the -1 term accounts for the fact that lensing magnifies the surface area and thus decreases the number density. Because of the different dependence on the slope α the signal of extinction and lensing can be separated simultaneously.

The SDSS galaxy-quasar cross correlation measurement (Scranton et al. 2005) is consistent with the $\alpha-1$ scaling and thus the dust contamination, if any, remains sub-dominant. Our dust models are consistent with this measurement, since the expected fractional contribution from dust extinction is $-\alpha/[2(\alpha-1)]\langle\delta\tau\delta_g^f\rangle/\langle\kappa\delta_g^f\rangle \sim -\alpha/(\alpha-1)\times(0.27, 0.11, 0.08, 0.03)$ for dust model A, B, C and D respectively. However, such measurement is already at the edge of providing interesting dust constraints. For instance, model A induces at $\theta = 0.01^\circ$ a negative correlation with amplitude $\sim 0.003\alpha b_g$, where b_g is the SDSS galaxy bias. This signal is already very close to the measurement uncertainty (Fig.7, Scranton et al. (2005) and the averaged $\langle\alpha\rangle \simeq 1$ from their table 2). In principle, by combining color and flux dependences of the galaxy-quasar cross correlation and the color-galaxy cross correlation, it will be possible to separate the contribution of lensing magnification, gray and reddening simultaneously [2]. The next generation of galaxy surveys such as LSST, ALPACA or PanSTARRS will provide foreground galaxy-quasars measurements that can achieve a S/N $\gg 10$. This will allow to discriminate the above dust models unambiguously, thus providing accurate constraints on the cosmic dust extinction and clustering properties.

4. CONCLUSIONS

Several new methods have been proposed for inferring the lensing magnification signal from a variety of correlation measurements. These involve SN Ia flux, the

[2] Private communication with Brice Menard.

fundamental plane and Tully-Fisher relation of optical galaxies. In this paper we have shown that contamination of cosmic dust extinction may severely degrade such measurements. As an example inhomogeneities in the cosmic dust distribution may limit the S/N of SN lensing measurements to $\lesssim 10$ level.

Billions of galaxies can be detected/resolved by the Square Kilometer Array[3] through the 21cm hyperfine transition line emission which is not affected by dust extinction. In such a case the only scatters other than intrinsic ones in the Tully-Fisher relation ($L \propto v_c^4$) are induced by lensing magnification, $L \rightarrow L(1+2\kappa)$. Therefore lensing reconstruction using these galaxies is an attractive possibility, since it is free of some systematics associated with cosmic shear such as shape distortion induced by point spread function.

On the other hand, spatial correlation measurements of SN fluxes or galaxy-quasar will constrain the amount of cosmic gray dust and its clustering properties to high accuracy. This will not only provide a better understanding of IGM dust physics, but also a valuable handing of dust contamination in the SN Ia Hubble diagram.

Acknowledgments—. We thank Brice Menard and Ryan Scranton for helpful discussions on dust contamination in SDSS samples. We are also thankful to Yipeng Jing, Peter Nugent and Alexandre Refregier for useful discussions. PJZ is supported by the One-Hundred-Talents Program of Chinese Academy of Science and the NSFC grants (No. 10543004, 10533030).

[3] SKA: http://www.skatelescope.org/

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